CDM afforestation for managing water, energy and rural income nexus in irrigated drylands

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Abstract

Rural livelihood in arid irrigated areas is hampered by water scarcity, land degradation and climate change. Studies showed a possibility to tackle these challenges by establishing tree plantations on marginal croplands as supported by the Clean Development Mechanism (CDM) forestation programs. Despite the environmental impact such projects would also affect the decision making of rural population by changing their land use activities, incomes and consumption structures. Thus, this study further analyzed the impact of CDM forestation on rural livelihood by considering rural interdependencies via wage-labor relations of agribusiness-operated farms and rural households in the Khorezm province and southern districts of Autonomous Republic of Karakalpakstan, Uzbekistan. We developed a farm-household dynamic programming model that jointly maximizes farm profits and rural households net incomes over a 15-years horizon under the scenario of decreasing irrigation water availability and plantation forestry with a seven year rotation period. The analysis showed that shortly following a land use change towards afforestation, the farm demand for rural households' labor would decline thus decreasing the household incomes. Yet, later on after harvesting tree plantations, in year seven, the farm benefits would be transmitted to rural households via access to cheaper fuelwood and leaves as fodder, as well as via improved land use activities. The availability of fuelwood from tree plantations would significantly decrease CO_2 emissions of households by substituting fossil fuels, while leaves would reduce expenditures for livestock fodder. These substitution effects would lead to the increase of income and in turn improve households' food consumption. Besides, given the low irrigation demand of trees, a conversion of marginal cropland to tree plantations would increase the irrigation water availability for other productive croplands. These changes would lead that tree plantations would increase in year seven profits of farmer (up to 39,200 USD) and net incomes of rural households (up to 12,700 USD). Whereas when only conventional land uses are followed the decline in water availability would reduce profits of farm (from 13,000 USD to 9,850 USD) and net incomes of rural households (from 11,900 to 10,500 USD) over the modeled period. Overall, we argue that the implementation of the short-term CDM forestation could help cushion repercussions of water shortages on rural livelihoods, sustaining energy, income and food security, as well as mitigating climate change in drylands.

Keywords: Sustainable rural development, dynamic farm-household model, short-rotation forestry, marginal croplands

1. Introduction

Over the last decades, global warming has been recognized as a major environmental issue (IPCC, 2007). In arid and semi-arid areas, the climate change could decrease irrigation water availability for crops thus reducing yields and affecting rural welfare (Fischer et al., 2007; IPCC, 2007). Conversion of degraded cropland parcels to tree plantations may be a land use option that improves land productivity, sequesters carbon (C) (Khamzina et al., 2012) and generate incomes (Djanibekov et al., 2012). Afforestation and reforestation implemented within the framework of the Clean Development Mechanism (CDM A/R) in low productive lands was stated as a cheaper solution than other offset schemes to mitigate climate change while enhancing sustainable development (Boyd et al., 2007; Palm et al., 2009).

Yet, the reports on economic impacts of such projects are scarce and show contrasting results. Xu et al. (2007) concluded that C sequestration tree projects could be regarded as a poverty alleviation measure in an underdeveloped area of Liping, China where rural poverty is widespread. Shuifa et al. (2010) also stated the vast potential of C forest sinks for climate change mitigation and increasing job opportunities in China. In contrast, Glomsrød et al. (2011) estimated economy-wide impact from establishing the CDM A/R in Tanzania, and found that such projects had weakness in fulfilling the objective of poverty reduction, and that the income transfer to rural areas would be unsubstantial.

These previous studies did not address the potential of C tree sinks for providing multiple products thus impacting incomes and commodities consumption structures. For instance, the integration of biofuel production in the objectives of forest C projects can decrease households' fossil energy expenditures and CO_2 emissions (Kaul et al., 2010). The foliage produced by fodder trees has the potential to improve feeding ration of livestock by providing cheaper, protein-rich fodder (Djumaeva et al., 2009; Lamers and Khamzina, 2010). Moreover, in a transition economy where the agricultural production is based on a bimodal farming system, the introduction of new land uses can alter rural interdependencies. The bimodal farming system, on the one hand, comprises large commercial farms with external economies of scale occurring through advantages in accessing inputs, credit and markets. The farms consume a negligible share, if any, of their own output and supply few, if any, of their own labor (Taylor and Adelman, 2003). On the other hand, there is a large number of semi-subsistence smallholders that often have incomes limited to sales of own-produced crops, and are bound to farm and non-farm employment. Labor contracts between farms and rural households can represent internal links existing in rural economies. Shively (2001) used an agricultural household model to examine rural labor markets, production, and consumption decisions and showed that farmers tended to hire labor with mixed wage and rent contracts. In the farm employment, significant redistribution of wage occurs in-kind, which, as an effective means of supporting food security of subsistence smallholders (Slesnick, 1996), can occur via transfers of various tree products. Cheung (1969) discussed that in presence of agricultural risks, sharecropping may emerge as the dominant contract arrangement. Sharecropping is the trade-off between risk sharing and incentive provision (Stiglitz, 1974). These types of transfers are necessary to achieve an efficient allocation of resources preferred by farms and smallholders.

In contrast to previous approaches, the explicit integration of farm and rural households in a single model that captures their interdependencies through agricultural contracts would broaden the understanding of the role of agricultural interrelationships in rural livelihoods and the multidimensional impact of introducing CDM A/R. We developed a dynamic programming model that integrated simultaneously farm and rural households decision-making. Determining the impact of CDM A/R at micro-level can contribute to the ongoing discussions on climate change mitigation and sustainable development options.

2. Methodology

2.1 Study area

The case study areas are Khorezm province and three southern districts of the Autonomous Republic of Karakalpakstan, namely Beruniy, Turtkul and Ellikkala, located in the Amu Darya River lowlands in Uzbekistan, Central Asia. These locations have an arid climate with an annual precipitation of around 100 mm. It occurs during the autumn and winter, hence crop cultivation is only feasible through irrigation. Near two million people reside in the study regions with about 70% being rural. The annual population growth rate is 1.7%. Agriculture accounts for about 35% of region’s GDP. Around 400,000 ha are arable of which 87% are leased by 7,500 commercial farms (as of 2010), while the rest mainly belongs to rural households. Near 20%-30% of croplands are considered low productive (MAWR, 2011). Major crops cultivated in commercial farms are cotton and winter wheat, covering 40% and 21% of their arable land respectively. These two crops are also the main crops planted on marginal lands. Both crops fall under the state policy of production targets (Djanibekov et al., 2010). According to cotton policy farmers has to allocate about 50% of their cropland for cotton and achieve cotton output based on soil-fertility level of their lands (Djanibekov et al., 2012). The state purchases from farmers the entire cotton harvest at prices lower than the potential border prices (Djanibekov et al., 2010). Wheres under the wheat production policy half of the wheat yield is purchased by the state at the prices three times below the local market price (Djanibekov et al., 2012). Rural households are mainly involved in gardening and livestock production in their backyards. Farms and rural households can be distinguished according to land size, income level, assets availability, labor availability, agricultural activities and requirement in fulfilling state policies (Djanibekov et al., 2012). The rural households depend on payments received in wage, in-kind, in-land, and through sharecropping from being employed at farm, as well as on income from selling part of agricultural products from own plots and on non-agricultural revenues.

2.2 The model

To investigate the impact of CDM A/R on rural livelihood, an integrated model of farm and rural household decision-making was developed based on the dynamic programming (DP) approach. The DP model supports the choice of optimal production planning of interdependent farm and rural households that maximize respectively their annual profits and net income in two situations: (i) business-as-usual (BAU) and (ii) CDM A/R introduced on marginal croplands (CDM). At the rural household level, agricultural household model is integrated linking production and consumption decisions. The model includes: (1) annual farming activities i.e. production, consumption, storage and selling to meet the state policy, food, fodder and energy requirements; (2) labor use on own household plots and hired labor for the on-farm field activities ; (3) structure of payments from the farm to rural households as the remuneration of labor. The model assumed fixed input and output prices. The model constraints included restrictions on: (1) the cropping area of farm and rural households; (2) annual cash availability for purchasing the inputs; (3) labor availability; (4) irrigation water availability; (5) households' food, fodder and energy consumption requirements; (6) the production targets for cotton; and (7) weight carriage of purchasing and selling products. The model comprised five main crops (cotton, winter wheat, rice, maize, and vegetables), eight by-products of these crops, one local tree species *Elaeagnus angustifolia* L. (Russian olive), four tree products, and eleven consumption commodities. The maximum storage period of crop and tree by-products was assumed to be six years, whereas vegetables did not have storage period.

We considered a 100-ha cotton-grain farm. The share of the farm marginal croplands was assumed to be 15 ha. According to the state production policy, the farm manager cultivated a half of the farmland with cotton. The farm employed additional labor from 15 rural households, each comprising six persons. Each household possessed 0.2 ha of arable land and two heads of livestock. For each working hour of the hired rural household member the farmer paid 0.4 USD in cash, and/or the equivalent value in-kind, and/or in-land given for crop cultivation. In the model, in-kind payments included crops and their by-products, as well as the by-products of trees.

These interdependencies between the farm and rural households are depicted in the module of payment structure (Fig. 1). The mathematical presentation of the model is given in Appendix A. More information on the interdependencies between farms and rural households in Uzbekistan was presented by Djanibekov (2008) and Veldwisch and Bock (2011).

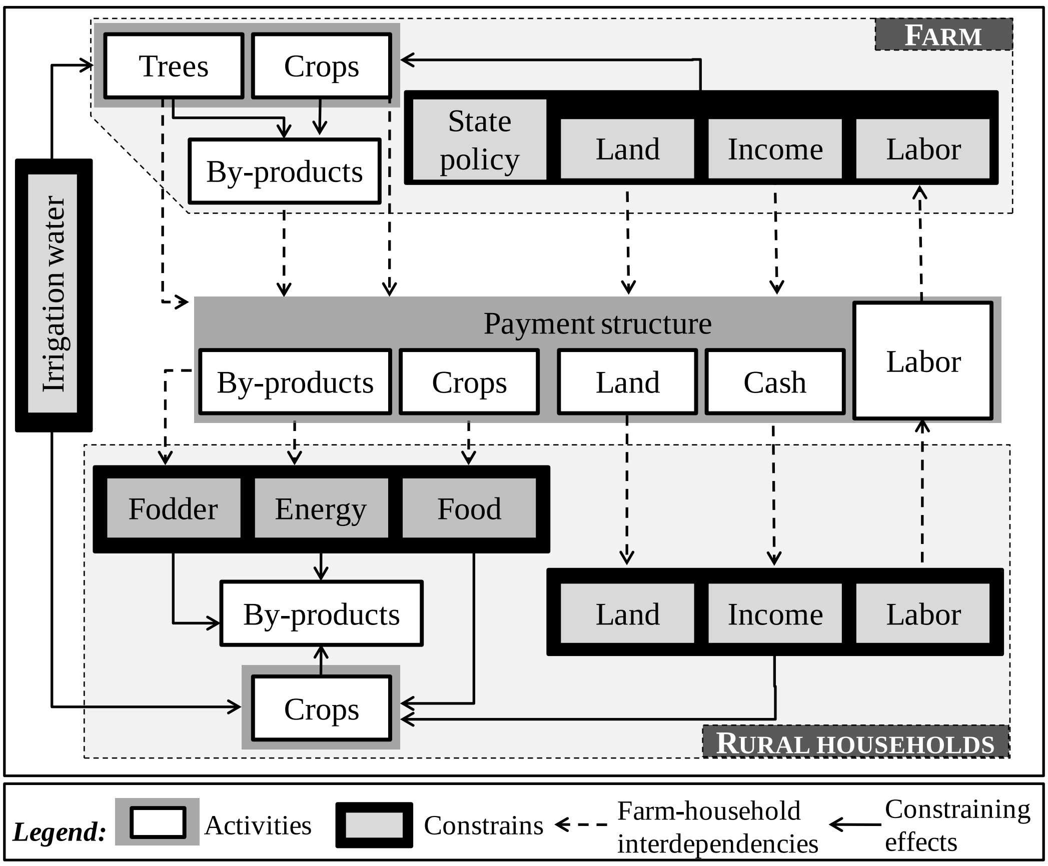


Figure 1: The structure of the farm and rural households model

2.3 Demand system

The per capita consumption of food, energy and leisure varies with respect to the income. Empirical observations demonstrated that a pronounced variation of income was typical in the transition countries and could not be captured by the linear Engel curves (Frohberg and Winter, 2001). Lau (1986) summarized a set of criteria for the selection of functional forms. There is a rather restricted amount of flexible functional forms which can be parameterized for the globally correct curvature without destroying their flexibility. Therefore, for the consumption component of the model we employed a demand system that reflects the influence of income changes on consumption patterns - Normalized Quadratic–Quadratic Expenditure System (NQ-QES). We applied a slightly modified version of Normalized Quadratic Reciprocal Indirect Utility Function (NQRIUF) proposed by Diewert and Wales (1988). The selected demand function is quadratic in income terms and proved to be reliable with respect to the forced theoretical conditions, convenient for the parameterization without imposing a computational burden (Ryan and Wales, 1999). NQ-QES is capable to reflect the driving influence of ample income changes on demand, more aligned with empirical evidence and particularly suitable for a policy analysis (Frohberg and Winter, 2001). In our model, the consumed products included food and non-food products and time spent by household members for leisure activities.

2.4 Data sources

The model's database comprising information on prices, input-output coefficients, income structure of households and other is summarized in Appendix B. Surveys of 140 farms and 400 rural households conducted in the study areas in 2010 provided information on food consumption, production technologies and costs, labor requirement, commodities transportation costs, as well as the use of tree products. Prices of food commodities, fodder, timber and fuelwood were collected through market survey in the same year. The costs associated with a small-scale CDM afforestation were assumed from Schlamadinger et al. (2007). Irrigation rates and timing followed the official recommendations (MAWR, 2001).

Due to the lack of data, the initial (uncalibrated) values for own- and cross-price elasticities of demand were adopted from Djanibekov (2008). The demand elasticities and demand system were calibrated according to the two-step approach suggested by Frohberg and Winter (2001). Information on per capita energy consumption was obtained from Kenisarin and Kenisarina (2007).

The tree species used in the model, *E. angustifolia*, had the highest net present value among the tree species growing on marginal croplands in study region of Khorezm (Djanibekov et al., 2012). The information on quantity and quality of products of *E. angustifolia* over seven years following the afforestation were obtained from the field study conducted on a 2 ha sized degraded cropland parcel with a planting density of 5,714 trees ha^{-1} (Khamzina et al. 2008; 2009a). The tree species required annually 800-1,600 m^3 ha^{-1} of irrigation water in the first two years and thereafter relied on groundwater. The prices of *E. angustifolia* foliage as fodder (not traded in the regions) were based on the foliar crude protein content referenced against that of dry alfalfa (Lamers et al., 2008). Timber production was not considered because the stem size does not develop sufficiently over seven years. We estimated the difference between households' CO_2 emissions from fuelwood burning and those from the combustion of coal, liquefied petroleum gas (LPG) (Carbon trust, 2011), and cotton stems (GuoLiang et al., 2008), commonly used in the study regions.

2.5 Scenario settings

The incomes of rural households in the face of reduced irrigation water availability were simulated for (i) BAU scenario and (ii) considering the introduction of CDM forestry with a 7-year rotation period on marginal cropland. The BAU scenario implied the allocation of part of the productive cropland and the entire marginal cropland for cotton cultivation. In the CDM scenario, the state production targets for cotton were released on the marginal cropland in favor of the short-rotation forestry.

The short-rotation strategy was motivated by the land tenure insecurity (Djanibekov et al. 2012) and rural demand for fuelwood (Vildanova, 2006). The CDM scenario considered annual harvest of fruits and the entire plantation harvest after seven years when also the temporary Certified Emission Reductions (tCER) were estimated. Thus the end of the rotation would correspond with the completion of the CDM project. Thereafter, the BAU settings with cotton cultivation on marginal croplands were reapplied.

The potential role of CDM afforestation in coping with the effect of declining irrigation water availability was estimated assuming the declining trend of the per hectare water supplies to arable land based on the regional statistics in 1992-2010 (Fig. 2) (MAWR, 2011). The overall irrigation, efficiency, considering the conveyance and application losses was according to Awan et al. (2011) and Tischbein et al. (2012). To understand the impact of short-term CDM forestation projects within long-term projections of declining water availability and growing rural population, the modeling scenarios were run over 15 years. The model was programmed in GAMS and solved via CONOPT3 solver.

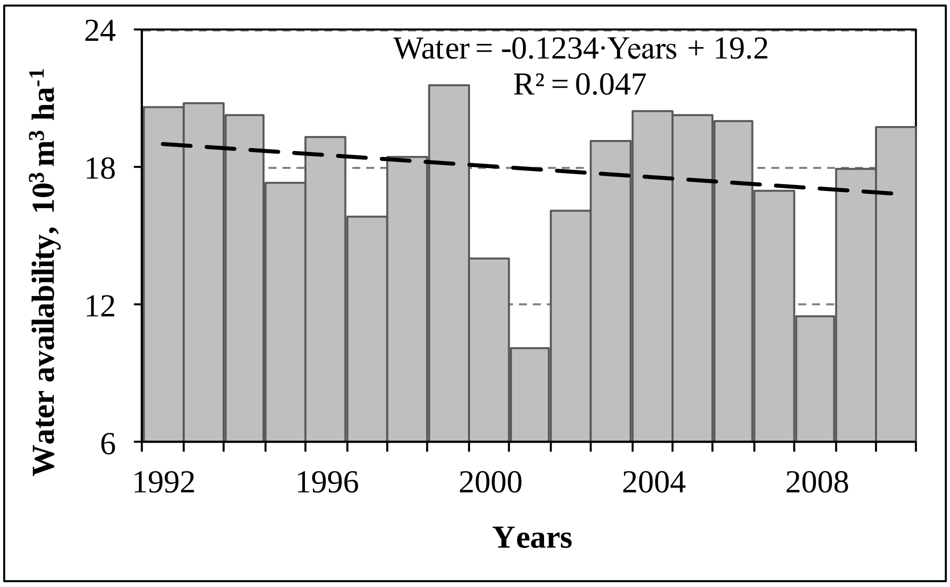


Figure 2: Water availability per hectare in the study regions during 1992-2010.

Source: MAWR, 2011

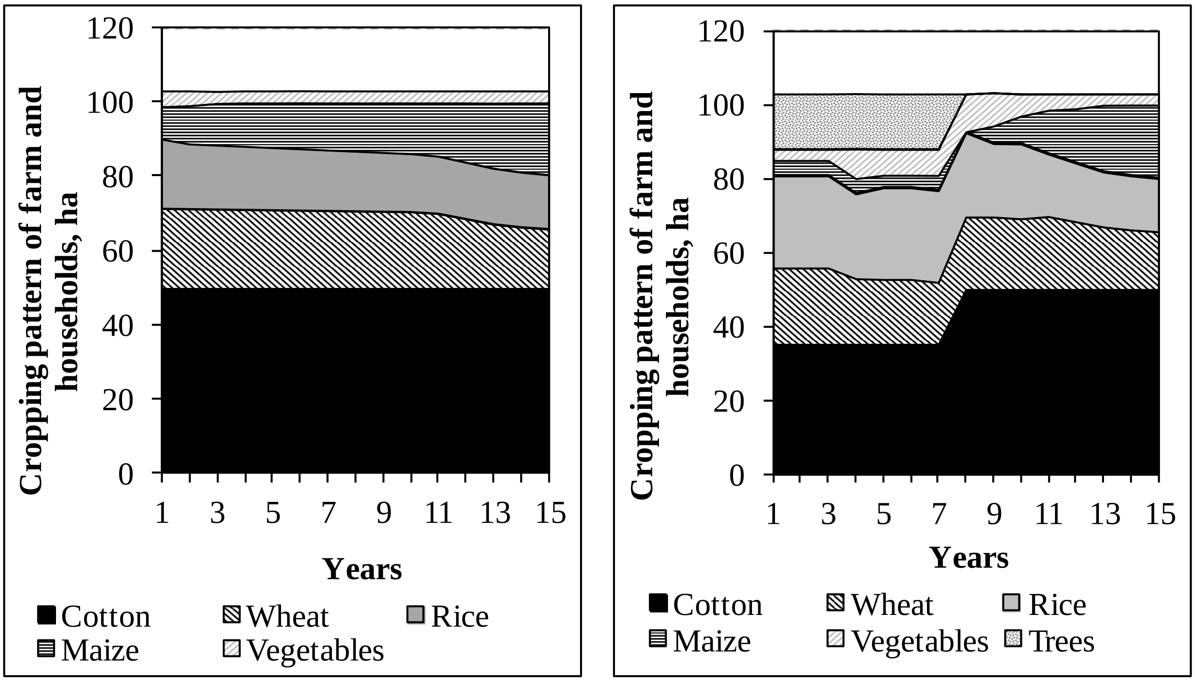
3. Results

3.1 Land use change

The decrease in water availability would trigger changes in farm's land use. Under the declining water supply in BAU scenario the cultivation area of wheat would decrease from 21 ha to 16 ha and that of rice from 19 ha to 14 ha over 15 years (Fig. 3a). The cropping pattern would shift towards less water demanding crops such as maize whose cropping area would increase from 9 to 20 ha. The area allocated to cotton would remain constant in accordance with the state policy.

The impact of afforestation in CDM scenario would go beyond the 15 ha of afforested marginal cropland. The shift from cotton to tree growing on the marginal land would reduce farm expenditures, thus allowing the investments to be diverted towards more costly but high-return crops, such as rice and vegetables, on productive croplands (Fig. 3b). The option of introducing the tree crop that requires only 3-30% of the irrigation demand of the annual crops (Djanibekov et al., 2012) on marginal cropland, would allow farmers to adjust their cropping patterns in productive areas towards more profitable though water demanding crops. Thus the rice cultivation area could be increased up to 25 ha and that of vegetables from 3 ha to 10 ha during the simulation period of 15 years.

Under both scenarios, the cropland area under maize would be increasing till year 15. Yet, cultivation of maize under the CDM scenario would decrease between years one and ten, and would not occur in year eight. Following the tree harvest in year seven, tree leaves and wheat and rice straw entirely substituted maize in feeding the livestock. Restoration of cotton cropping practices after the clear cut would trigger once again changes in the land allocation to crops. The area for maize cultivation would increase from 0 to about 20 ha, while the rice and vegetable areas would again decline from 19 to 9 ha and from 10 to 3 ha, respectively. In both scenarios the land use changes would be observed only on farm fields, whereas the cultivation of vegetables in rural households would remain unchanged.



(a) (b)

Figure 3: Cropping pattern of farm and rural households in BAU (a) and CDM (b) scenarios over 15 year simulation period.

3.2 Farm employment

Given that less labor is needed for tree plantation management than for annual cropping activities, the CDM afforestation may result in an agricultural labor discharge (Fig. 4). The households working hours would be decreasing during the first seven years (from 48,800 to 44,500 hours, compared to BAU scenario of 55,700 to 55,000 hours). At the tree plantation harvest, the demand for labor at farm would increase for the labor-intensive operations such as felling and sectioning the woody parts and separating the fruits and foliage. Increase in the labor demand could mean additional incomes for rural households due to a diversification of payments in-kind offered by the farmers, including fuelwood and tree foliage (Fig. 5b).

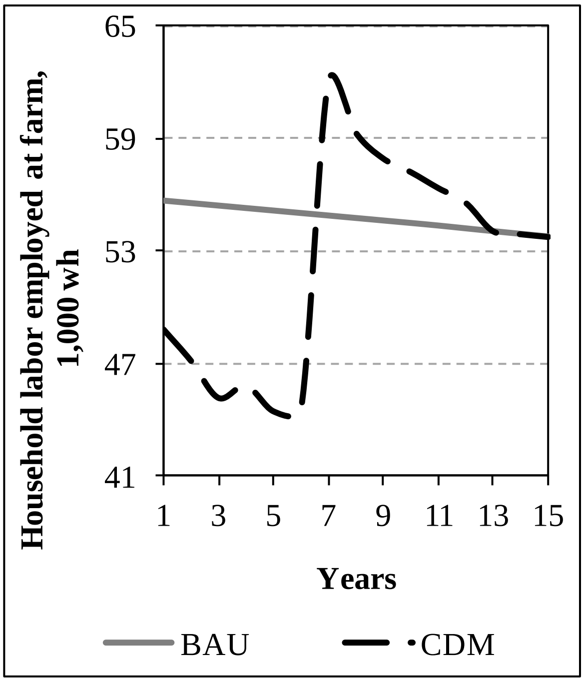
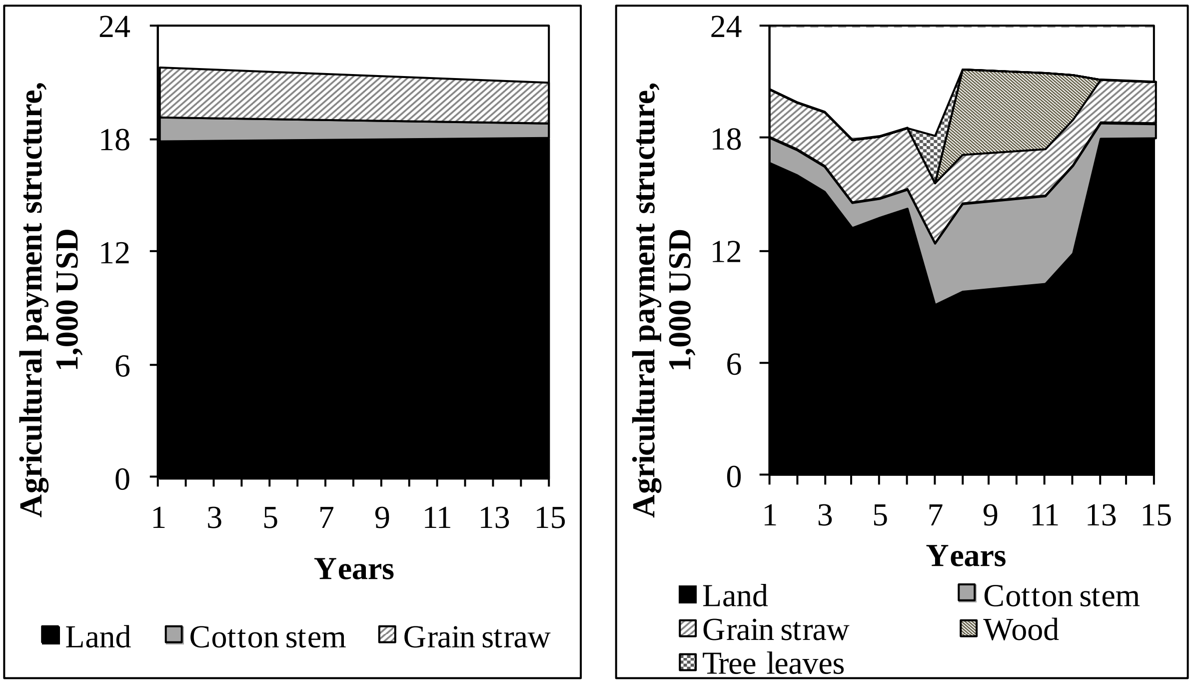


Figure 4: Employment of rural households at farm in BAU and CDM scenarios over 15 year simulation period.

The changes in payment structure may decrease further the pressure on households' capital. In the CDM scenario, the payment structure would differ year by year as opposed to BAU. In-kind payments in form of fuelwood would account for one of the main household income sources from working on farm. The cropland area allocated by farmer to his employees as payment would reduce for six years after the tree harvest, from 14 ha to 11 ha. In-kind payments in form of cotton stem would increase after the tree harvest along with the restoration of cotton cultivation on marginal land. In the BAU scenario, the payments in form of land would increase with the decreasing water availability, whereas the payment in cotton stem and grain straw would decline (Fig. 5a). In both scenarios, the area of farmland used for payment to rural households would increase in response to declining crop profits due to decreasing water availability.



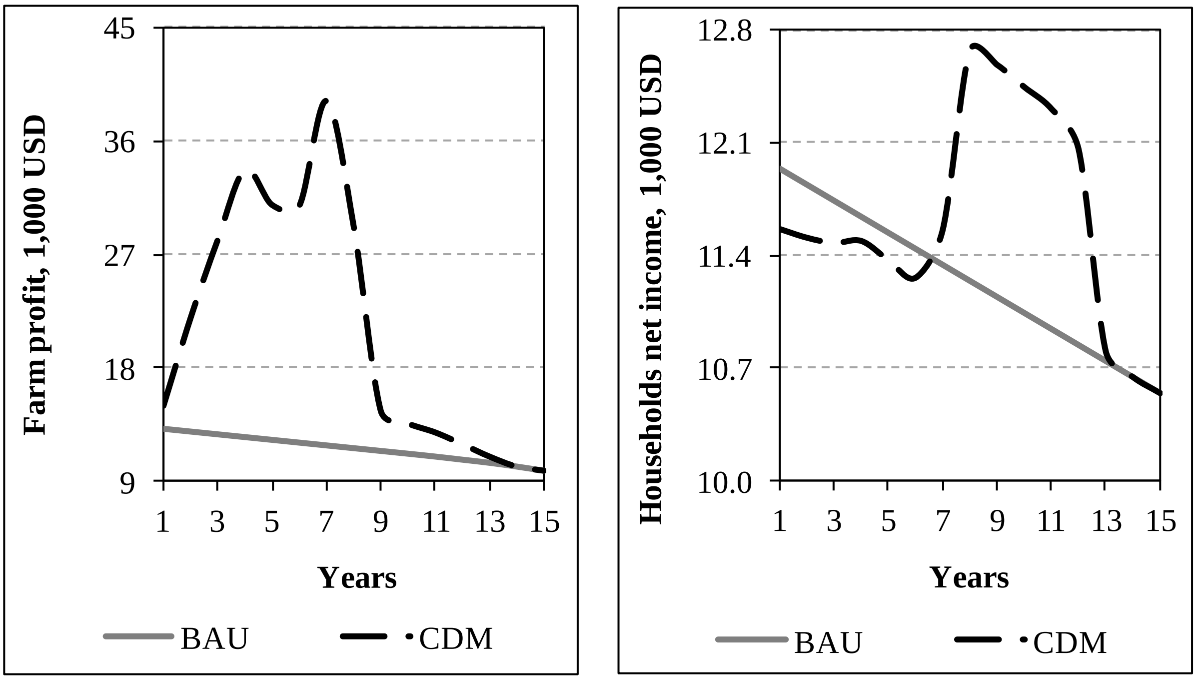
(a) (b)

Figure 5: The structure of farm-to-rural households payment in BAU (a) and CDM (b) scenarios over 15 year simulation period.

3.3 Farm and rural households incomes

Under BAU scenario, the decline in water availability would reduce the farm's annual profits (from 13,000 USD to 9,850 USD) as well as the net incomes of rural households (from 11,900 to 10,500 USD; Fig. 6a and 6b). In contrast, under the CDM scenario, incomes of both, the farmer and rural households, would increase through the harvest of non-timber products and shifts in cropping pattern towards higher return crops. Particularly farm profits would increase (up to 39,200 USD) since afforestation of marginal croplands would bring positive returns as opposed to the state-regulated cotton cultivation on marginal land that would result in losses. The farm profits would increase in year seven also due to the low management costs of tree plantations. The net incomes of rural household would decrease during seven years of CDM afforestation due to reduced farm employment but would grow with the harvest of trees in year seven.

The shifts in the payment structure (see Section 3.2) would allow households to reduce their expenditures for purchasing expensive animal fodder and domestic energy. The tree foliage and fuelwood could substitute or complement respectively grain straw as livestock fodder and coal and LPG as domestic energy sources beyond the duration of CDM A/R. Following the completion of CDM project, the incomes of farm and rural households would diminish to the levels observed under the BAU scenario.



(a) (b)

Figure 6: Farm profit (a) and rural households' net income (b) in BAU and CDM scenarios over 15 year simulation period.

3.4 Food consumption of rural households

The income-responsive demand function incorporated into the model determines if the household consumption levels are responsive to the income. We analyzed the changes in the consumption of three main food products: wheat, rice and meat. The calibrated income elasticities of these products were 0.42 (wheat), 0.36 (rice) and 0.7 (meat). Declining household incomes under the BAU scenario would result in 5% decline in per capita consumption of these three commodities over 15 years (Fig. 7). The CDM afforestation scenario showed reduced rural household incomes in the first seven years, and consequently a lower consumption of the food products than in the BAU case. However, in the year of the tree harvest and the end of CDM commitment, the increase in farm incomes due to tCERs would be also transmitted to rural households. This in turn would increase the per capita consumption of the food products above the levels observed in the BAU scenario. In this case, the largest change would occur in meat consumption measuring 12% increase from the initial level of 32 kg capita and exceeding the meat consumption in the BAU scenario by 14%. The consumption of wheat and rice in the CDM scenario increased by 1-2% from the initial levels in year 8 and was about 4% higher than that under BAU. Six years after completing the CDM project, the levels of food consumption in both scenarios would equalize.

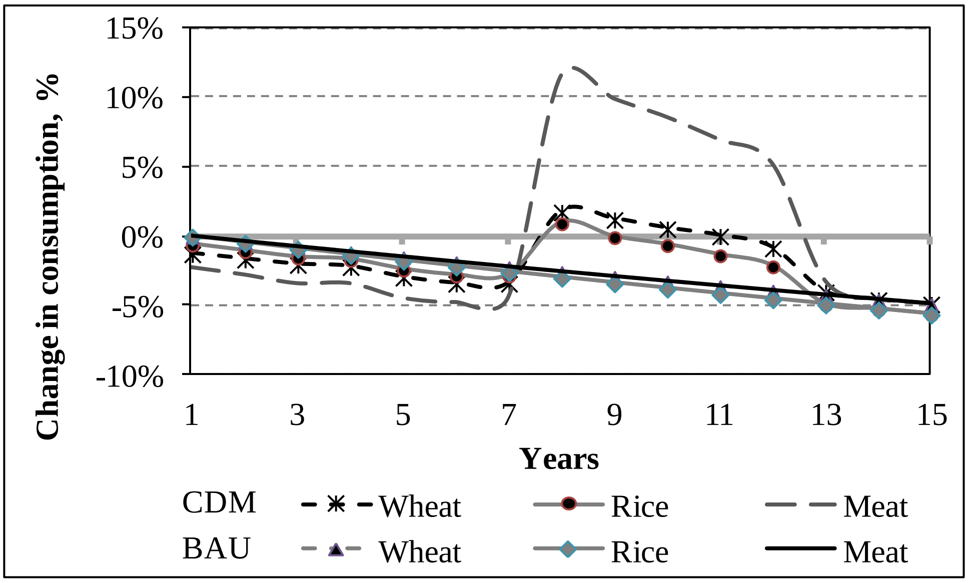


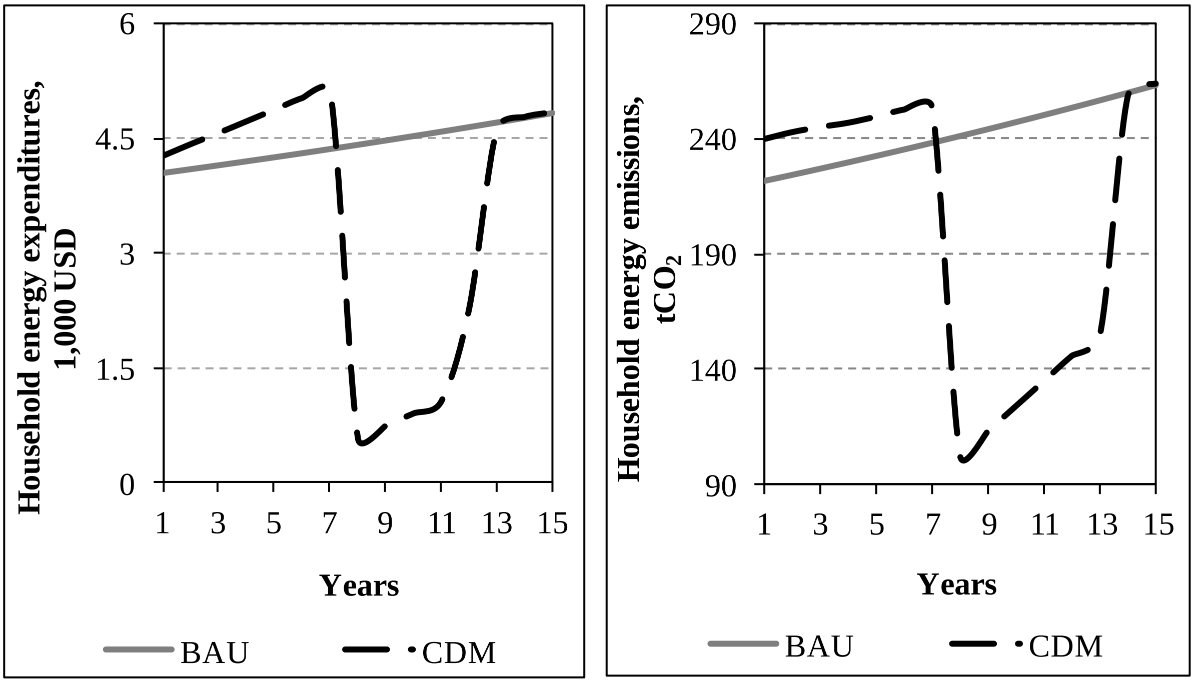
Figure 7: Changes in the consumption of main food commodities by rural households in BAU and CDM scenarios over 15 year simulation period.

Note: 0% is initial consumption level

3.5 Energy security and climate change mitigation

CDM afforestation over the seven years on marginal farmlands (15 ha) would sequester 3,532 tCO_2, worth of 8,732 USD. The highest returns would be obtained from fruit production (78,950 USD), followed by that of fuelwood (33,724 USD). Considering the maximum sequestration rate of 16,000 tCO_2 $year^{-1}$ for the small-scale CDM A/R projects and the farm size of about 100 ha of which 15 ha are marginal, the CDM project with *E. angustifolia* afforestation would have to involve 32 farms.

The model output in BAU scenario showed the increase in total energy costs of rural households from 4,000 USD to 4,800 USD due to the population growth (Fig. 8a). During the CDM project period, the decreased cultivation of cotton would result in the reduction of cotton stem transfer as payment in-kind. This would raise the total 7-year expenditures for energy by 3,540 USD and CO_2 emissions by 119.3 tCO_2 due to the increased usage of coal and LPG, as compared to the BAU situation (Fig. 8a and 8b). After the tree harvest, the substitution of fuelwood for LPG, coal, and cotton stem would reduce energy expenditures and CO_2 emissions of rural households. Thus, the CDM A/R of 7-year duration period culminating in the fuelwood harvest would allow the households to save in total 17,200 USD over the next six years (from year 8 to 13). Moreover, the stored fuelwood could partially substitute for coal and LPG beyond the duration of CDM A/R, reduce the emissions in total by 720.7 tCO_2 as compared to the BAU scenario.



(a) (b)

Figure 8: Rural households' domestic energy expenditures (a) and energy emissions (b) in BAU and CDM scenarios over 15 year simulation period.

4. Discussion

The impact of climate change, land degradation, and water scarcity can stagnate agricultural yields in developing countries affecting rural incomes and food security (Holden and Shiferaw, 2004; Fischer et al., 2007). Approaches addressing these problems must deal with the core issue of incentivizing decision makers to respond positively to a new policy instruments. While innovative technologies and improved infrastructure remain important coping options, their implementation is difficult in the transition countries due to high initial investments and market failures (Jaffe et al., 2005). In this respect, implementing CDM A/R on marginal croplands is viewed as a promising option for the mitigation of climate change, land rehabilitation, and improvement of the water use efficiency and the rural livelihood (Boyd et al., 2007; Palm et al., 2009).

4.1 Rural incomes and consumption

The allocation of degraded cropland to tree plantations in lieu of cotton alters farm and rural household activities thus affecting the agricultural production and food and energy consumption of the rural population. According to the evaluation of CDM reforestation project in Guangxi Watershed Management in China (Gong et al., 2010), the CDM project improved farmers' incomes by conversion of barren lands to tree plantation. Xu et al. (2007) in the case of China likewise showed that improved the economic conditions of the population after shifting agricultural land to the C forest project, particularly for families with higher income and more economic resources (such as the commercial farms in our case).

Our assessment indicates that the establishment of a tree plantation can cushion mid- and long-term implications of declining water availability. Potential CDM A/R project under irrigated agriculture settings improved incomes of both, farmer and subsistence rural households. In response to improved incomes, per capita food consumption of rural households would also increase. Yet, waiting period is required because in the first years after afforestation the labor demand for farm fields would decline. Consequently, additional measures would be required to cushion losses in the initial years considering that the majority of rural population in Uzbekistan depends on incomes from farm employment.

4.2 Benefit transfer

The modeling analysis indicated the importance of non-timber products as co-benefits of CDM A/R. According to Hyde and Köhlin (2000) the effect of change in household income on the consumption of forest products was small. In Uzbekistan, farmers are important gatekeepers for livelihood resources of rural households (Veldwisch and Bock, 2011). This interrelationship is rooted in the agricultural payment structure, mainly via payment in-kind and because the monetary value of payments in form of crop and tree products are positively correlated with their price (Ito and Kurosaki, 2009). Tree products can be transferred to rural smallholders who, although not participants of the CDM project, indirectly benefit from the engagement in the production operations of the participating farms. More specifically, the inclusion of tree fodder and fuelwood into the payment structure can decrease feeding cost for livestock (Djumaeva et al., 2009) as well as the expenditures for energy. Fuelwood production on marginal croplands could secure energy availability in rural areas of Uzbekistan, where reduced access to gas supplies is compensated through illegal logging of forests (Vildanova, 2006).

4.3 Sustainability

To be effective land use policies in irrigated agricultural settings need to take into account the interdependent natural resources of land, water, energy, and their impact by climate change. In study regions where water supplies for agriculture frequently fluctuate and follow the declining trend (MAWR, 2011), the introduction of CDM A/R on marginal croplands has the potential to increase rural livelihood and cushion the repercussions of water scarcity due to the change in the farmland use towards less irrigation water demanding tree plantations. Irrigation water not used by tree plantations can be applied to commercially important crops on fertile croplands (Khamzina et al., 2012), and thus augmenting returns from crops. Moreover, substantial C benefit can be obtained from using marginal croplands for growing short-rotation tree plantations and substituting or complementing fossil fuels by the fuelwood thus increasing households' net incomes and reducing CO_2 emissions. When tree growth rates are high and several rotations are implemented, the opportunities for C reductions can act as a substitute of fossil fuel (Kaul et al., 2010). The other benefits of afforestation in Uzbekistan prerviously demonstrated but not considered in our assessment is the improved soil quality of afforested plots due to the accumulation of organic C and macronutrients (Khamzina et al., 2009b). Thus, afforestation of marginal croplands presents an option for hedging the agricultural production risks by diversifying farm activities as well as all land-based sources of rural incomes. The main barriers to establish CDM A/R, i.e., large transaction and establishment costs (Thomas et al., 2010), could be covered in the short-run period by annual returns from fruits of *E. angustifolia* (Djanibekov et al., 2012).

5. Conclusions

In our study, we investigated CDM A/R as a land use option that is able to address the issues of sustainable development, mitigation of climate change effects and adaptation to water scarcity through economic incentives. Capturing the existing interrelations in the bimodal farming system provided a more detailed overview of the impacts of the land use change towards forestry in marginal cropland areas. Based on the farm and rural households' payment relationships we conclude that the benefits from CDM A/R farm incomes can be transferred to rural smallholders who are directly engaged in the farm operations. The results of the developed dynamic programming model indicated the initial decline in on-farm demand for rural labor following afforestation, affecting the rural incomes. Yet, at the end of the plantation rotation period the tree harvest can generate sufficient revenues to compensate these losses. The multiple products supply characteristics of tree species selected for CDM A/R would contribute to the improved agricultural contracts structure through in-kind payments. Via access to fuelwood as a cheaper energy resource, as well as leaf fodder as a cheaper, protein-rich feeding supplement, the rural households would be able to divert part of their capital and resources to other agricultural and non-agricultural activities. Furthermore, given the low irrigation requirement of trees, a conversion of marginal croplands to tree plantations can increase the water availability for other fields, and secure rural incomes against the declining water availability.

Launching the CDM A/R cannot be afforded by single farmers who therefore would have to cooperate to reduce the associated costs. Further research should analyze how cooperative action among farmers can be organized, the role of institutions enabling economic sustainability of CDM A/R on marginal croplands, and the benefit transfer to rural smallholders.

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Appendix A: Mathematical representation of the model

The model's objective function (Obj) is maximization of farm's profit (V) and rural households' net income (V^o) over 15 years period (t) [Eq.1]:

$$\text{Max Obj} = \sum_{t=1}^{15} (V_t + V_t^o)$$

The model solves subject to a set of system, farm- and households-specific constraints.

Farmer's profit value comprises marketed amount of *i* crops (S) and *z* byproducts ($\bar{S}$), purchased amount of *a* inputs (E) multiplied with their respective prices (p, $\bar{p}$, $\bar{\bar{p}}$ and $\dot{p}$) as well as other costs related to growing *j* crops/trees (u) on farmland (X) [Eq.2].

$$V_t = \sum_i p_i \cdot S_{it} + \sum_z \bar{p}_z \cdot \bar{S}_{zt} - \sum_a \bar{\bar{p}}_a \cdot E_{at} - \sum_j u_j \cdot X_{jt}$$

Households' net income value consists of the value of marketed and purchased *i* crop products (S^o, $\bar{S}^o$) and *z* crop/tree byproducts (B^o, $\bar{B}^o$), *a* purchased inputs (E^o), *e* purchased energy resources ($\bar{\bar{B}}^o$) at their respective prices (p, $\bar{p}$, $\bar{\bar{p}}$ and $\dot{p}$), income from non-agricultural activities (M) at wage rate ($\bar{s}$), cash received from farmer (R) as well as other costs of *j* crop cultivation activities (u^o) on household plots (X^o) and on land received from farmer ($\bar{X}^o$) [Eq.3]:

$$V_t^o = \sum_i p_i \cdot (S_{it}^o - B_{jt}^o) + \sum_z \bar{p}_z \cdot (\bar{S}_{zt}^o - \bar{B}_{zt}^o) + \bar{s} \cdot M_t - \sum_a \bar{\bar{p}}_a \cdot E_{at}^o - \sum_e \dot{p}_e \cdot \bar{\bar{B}}_{et}^o + R_t - \sum_j u_j^o \cdot (X_{jt}^o + \bar{X}_{jt}^o)$$

The farm's labor balance defines that the farm uses his own labor (b) and labor hired from households (N) for *j* crop cultivation (X) that demands (k) of labor hours [Eq.4]:

$$\sum_j k_j \cdot X_{jt} \leq b_t + N_{ht}$$

In this respect, households' labor balance defines the interactions with farmer: households can use their available labor hours (b^o) to cultivate *j* crops on their own plots (X^o) and/or on land received from farmers ($\bar{X}^o$) each demanding a certain working hours (k^o), to be hired for farm activities (N) and/or off-farm activities (M), and to consume their time for leisure (D^o= consumption per capita, pop = number of household members) [Eq.5]:

$$\sum_j k_j^o \cdot (X_{jt}^o + \overline{X}_{jt}^o) + N_t + M_t + pop \cdot D_{leisure,t}^o \leq b_t^o$$

The interactions between farm and households are further determined by the household labor hours hired (N) at wage agreed (s) and the structure of payments which includes cash (R), *i* crop products in-kind (C), *z* crop/tree byproducts in-kind ($\overline{C}$), land (G) at their respective prices (p, $\overline{p}$, g) [Eq.6]:

$$s \cdot N_t = R_t + p_i \cdot C_{it} + \overline{p}_z \cdot \overline{C}_{zt} + g \cdot G_t$$

Land constraint of farm defines that the land available (q) can be used for *j* crop/tree growing activities (X) and/or given as remuneration (G) for hired labor to households [Eq.7]:

$$\sum_j X_{jt} + G_t \leq q$$

Accordingly, total area of household plots (q^o) determines *j* crop cultivation area [Eq.8]:

$$\sum_j X_{jt}^o \leq q^o$$

In addition, households can cultivate land received as remuneration for provided labor (G): its cultivation area ($\overline{X}^o$) should exceed the area of received land (G) [Eq.9]:

$$\sum_j \overline{X}_{jt}^o \leq G_t$$

The water constraint applies to the entire modeled system: water used on farms fields (X), household plots (X^o), household operated farm fields (G) at respective irrigation rates (W, W^o and $\overline{W}$) should not exceed the amount of water available in the system (w) [Eq.10]:

$$\sum_j W_{jt} \cdot X_{jt} + \sum_j W_{jt}^o \cdot X_{jt}^o + \sum_j \overline{W}_{jt} \cdot \overline{X}_{jt}^o \leq w_t$$

The cotton production policy defines that the farm's cotton cultivation area (X_{cotton}) should not be less than the assigned target area (F) [Eq.11]:

$X_{cotton,t} \geq F_t$

The farm's product balance defines that *i* crop/tree products harvested at yields (Y) with respect to the water application rate (W) and cultivated area (X) can be marketed (S), used as payment in-kind to households (C) or stored (H) for the next period [Eq.12]:

$$\sum_j Y_{jit} \cdot X_j = S_{it} + C_{it} + H_{it} - H_{it-1}$$

Similar applies to the farm's crop/tree byproduct balances.

The households' product balance defines that *i* crops harvested on household plots and on land received from farm at yields (Y^o, $\overline{Y}^o$), that depend on water application rate (W^o), and cultivated area (X^o, $\overline{X}^o$) as well as received as payment in-kind (C) and purchased (B^o) can be sold (S^o), consumed (D^o) or stored for the next period (H^o) [Eq.13]:

$$\sum_j Y^o_{jit} \cdot X^o_{jt} + \sum_j \overline{Y}^o_{jit} \cdot \overline{X}^o_{jt} + C_{it} + B^o_{it} = S^o_{it} + pop \cdot D^o_{it} + H^o_{it} - H^o_{it-1}$$

Similar applies to the households' crop/tree byproduct balances.

In this respect, the energy use balance defines that the amount of energy products received from farmer as payment in-kind (C), reserves from previous periods and purchased ($\overline{\overline{B}}^o$) can be consumed ($D^o$), stored ($H^o$) and/or sold ($S^o$) when converted into energy units via their energy content parameters (d, $\overline{d}$) [Eq.14]:

$$\sum_i d_{i,energy} \cdot (C_{it} + H^o_{it-1}) + \sum_e \overline{d}_{e,energy} \cdot \overline{\overline{B}}^o_{et} = pop \cdot D^o_{energy,t} + \sum_i d_{i,energy} \cdot (H^o_{it} + \overline{S}^o)$$

Finally, the households' demand function of *i* products (D^o per capita) comprises linear (α) and non-linear (β) terms with respect to the households' net income value (V^o) [Eq.15]:

$$D^o_{it} = \alpha_i \cdot \frac{{V^o_t}^2}{p_k \cdot \sum(p_k \cdot \beta_k)} + \beta_i \cdot \frac{V^o_t}{\sum(p_k \cdot \beta_k)}$$

where <u>*k*</u>=*i* for crop/animal products, nonfood products, energy and leisure. The households' total consumption expenditure is equal to their net income (V^o_t) [Eq.16]:

$$pop \cdot \sum_i p_{it} \cdot D^o_{it} = V^o_t$$

Appendix B: General characteristics of model database

Basic information used in the model		**Food**	Price, USD t^{-1}	Food consumption, kg cap^{-1} y^{-1}	
Farm size, ha	100	Wheat	227		164
Area of farm marginal croplands, ha	15	Rice	682		24
Arable area of rural household, ha	0.2	Maize	227		32
Number of rural households	15	Vegetables	455		210
Family size of rural household	6	Meat	3,636		32
Livestock per rural households	2	Eggs	103		74
		Milk	247		160
Agricultural wage, USD wh^{-1}	0.4	**Fodder**	Price, USD t^{-1}	Nutrient content ME, MJ kg^{-1} DM	CP, g kg^{-1} DM
Initial funds in farm, USD ha^{-1}	650	Straw	33	6	74
Initial funds in household, USD hh^{-1}	2,000	Maize stem	30	7	95
		Foliage	53	8	227
Share of energy expenditures, %	3	**Energy**	Price, USD t^{-1}	Energy content, MJ t^{-1}	
Share of non-food expenditures, %	33	Cotton stem	36		17,007
Carbon price, USD $tCER^{-1}$	4.76	Coal	45		21,000
Annual energy cunsumption, MJ cap^{-1}	24,700	LPG	682		46,150
		E. angustifolia fuelwood	41		19,000

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